HPAC Info-dex 2

Engineering Basics

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The articles in this section were selected by HPAC's Engineering Editor based on their generic and fundamental nature. Engineering Basics is intended to be used by engineers, contractors, and facility managers to brush up on engineering fundamentals across a wide range of subjects pertaining to mechanical systems design, building science, and product selection. This year's selections are as follows:

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Water Vapor Migration and Condensation Control in Buildings

The basics of water vapor analysis and control

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Water vapor is the gaseous form of water and is an invisible source of many problems in today's buildings. This article will provide a basic understanding of how water vapor transport occurs, when it condenses, and when it can cause damage and health problems.

Water vapor can travel through building structures by:

- Diffusion caused by vapor pressure differentials.
- Air flow created by temperature differentials.
- Air flow created by mechanical systems.
- Rain penetration through intake louvers.

To begin with, psychrometric conditions on the inside of a building are usually different than the outside conditions. The difference in psychrometric properties results in a vapor pressure differential from inside to outside, which sets up the driving force for water vapor diffusion. The direction of water vapor flow is from high vapor pressure or high humidity to low vapor pressure or low humidity. In colder climates, such as the northern U.S. and Canada, the amount of water vapor in the outside air is very low (low vapor pressure) and is less than the building inside air (high vapor pressure). Thus the water vapor diffusion is from inside to outside. In warmer climates with short heating seasons, the water vapor drive is from outside to inside due to the drying effect of indoor air conditioning. If the water vapor condenses in the wall or roof section and does not have the opportunity to dry out, then over a period of time, there will develop an accumulation of water that could cause damage and/or mold and mildew. Keep in mind that this is a dynamic situation where condensation may occur during part of the day and evaporation during another part. The engineer's job is to design the cavity so that condensation does not occur, does not occur frequently, or only occurs in a safe region, such as an air space with drainage.

The terms and equations for water vapor transmission or diffusion are listed in the accompanying sidebar. Equations 6 and 7 are the vapor diffusion equations used to calculate the amount of water vapor that passes through the wall or ceiling cavity. The overall coefficient of vapor transmission, M, is determined by adding the resistances to vapor transmittence for the construction materials (and air films) and then taking the inverse of that summation. This procedure is illustrated in Equations 4 and 5. The inside and outside vapor pressures can be determined from test data or by using typical psychrometric data for that region. If there is concern over the amount of water vapor diffusion or concern over condensation in the cavity, the engineer may need to install a vapor retarder.

The ASTM definition of a vapor retarder is a material with a vapor performance (PERM) of 1.0 or less. The resistance to vapor transmittance is illustrated in Equation 1. The resistance to vapor transmittance is the inverse of the PERM value; therefore, the lower the PERM value, the greater the resistance to water vapor diffusion. Some state codes require a PERM rating of less than 1.0 to qualify as a vapor retarder.

TABLE 1—Typical vapor retarder materials.

Material	Thickness, in.	PERM*
Aluminum foil	0.00035	0.05
2-mil polyethylene	0.002	0.16
4-mil polyethylene	0.004	0.08
6-mil polyethylene	0.006	0.06
Butyl rubber elastomer	0.015 to 0.04	0.02
Vapor retarder paint	0.0031	0.45
Kraft facing on glass fiber batts	0.0118	0.40

*Typical PERM values can be obtained from the *1997 ASHRAE Handbook of Fundamentals* or the ASTM book, *Moisture Control in Buildings*.

Water vapor diffusion

Water vapor diffuses through many building materials other than metals when a vapor pressure difference exists across the construction. One consensus that seems to have been reached is that vapor retarders are needed in cavity walls and ceilings. In cold and moderate climates, the vapor retarder is placed on the indoor side of the cavity. This is because the water vapor flow is from inside to outside (the inside is the higher vapor pressure). In some warm climates that have a short heating season, the vapor retarder is placed on the outside of the cavity because air conditioning of the indoor air dries the air, thus lowering the indoor vapor pressure below the outdoor vapor pressure. In some warm climates, vapor retarders are installed on both the

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Water vapor diffusion through materials of construction

Terms

M = Overall coefficient of vapor transmission or overall PERM value (some references also use M to designate the PERM value for individual materials), grains water vapor/hr-sq ft-in. Hg

PERM = Permeance (this value varies with material thickness), grains water vapor/hr-sq ft-in. Hg

PERM-IN. = Permeability (this value can be found in tables without the knowledge of material thickness), grains water vapor-in./hr-sq ft-in. Hg

$Pw_1 - Pw_2$ = Difference of vapor pressure between ends of the flow path, in. Hg

REP = Resistance to vapor transmittence, in. Hg-sq ft-hr/grains water vapor

W = Total mass of water vapor transmission per unit area in unit time, grains water vapor/hr-sq ft

Equations

1) $\text{REP} = \dfrac{1}{\text{PERM}} = \dfrac{1}{\text{PERM} - \text{IN./in. thick}}$

2) $\text{PERM} = \dfrac{1}{\text{REP}} = \dfrac{\text{PERM - IN.}}{\text{in. thick}}$

3) $\text{PERM - IN.} = \text{PERM} \times \text{in. thick}$

4) $M = \dfrac{1}{\frac{1}{\text{PERM}_1} + \frac{1}{\text{PERM}_2} + \frac{1}{\text{PERM}_3} + \frac{1}{\text{PERM}_{(etc.)}}}$

5) $M = \dfrac{1}{REP_1 + REP_2 + REP_3 + REP_{etc.}}$

6) $W = M \times (Pw_1 - Pw_2)$

7) $W = \dfrac{1}{\sum \text{REP}} \times (Pw_1 - Pw_2)$

Psychrometrics used to determine vapor pressures

Terms

$MW_{\text{dry air}}$ = Molecular weight of dry air, 28.9645 lbm/lb-mole

$MW_{\text{water vapor}}$ = Molecular weight of water vapor, 18.01534 lbm/lb-mole

P_{abs} = Total absolute pressure, in. Hg

P_{bar} = Barometric pressure, in. Hg

P_{gauge} = Gauge pressure (sometimes called duct pressure or pipe pressure), in. Hg

Pa = Partial pressure of the dry air in the mixture, in. Hg

Pw = Partial pressure of water vapor in the mixture, in. Hg

Pws = Pressure of saturated pure water, in. Hg

RH = Relative humidity, percent

T_{DB} = Dry bulb temperature, F

T_{WB} = Wet bulb temperature, F

T_{DP} = Dew point temperature, F

W = Absolute humidity, lb water vapor/lb dry air

Equations

8) $P_{\text{abs}} = P_{\text{bar}} + P_{\text{gauge}}$

9) $P_{\text{abs}} = Pa + Pw$

10) $\text{RH} = (Pw/Pws) \times 100$

11) $W = (Pw/Pa) \times (MW_{\text{water vapor}}/MW_{\text{dry air}}) = (Pw/Pa) \times 0.62198$

12) Pw can be determined using the equations or can be found using the tested dew point temperature and the steam tables.

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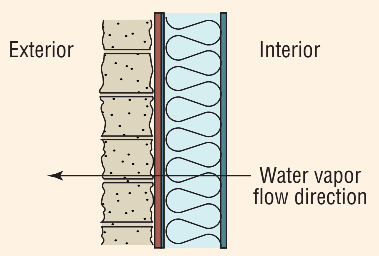
TABLE 2—Psychrometric computer analysis for 70 F air temperature.

ELEVATION ABOVE SEA LEVEL	0.	FEET
BAROMETRIC AIR PRESSURE	29.9210	Inches Hg.
DUCTWORK OR GAGE PRESSURE	0.0000	ATMOSPHERIC
TOTAL ABSOLUTE PRESSURE	29.9210	Inches Hg.
DRY BULB AIR TEMEPERATURE	70.0000	F
WET BULB TEMPERATURE	58.3953	F
DEW POINT TEMPERATURE	50.4239	F
ADIABATIC SATURATION TEMPERATURE	58.4111	F
RELATIVE HUMIDITY	50.0000	%
PERCENT SATURATION	49.3766	%
ACTUAL AIR FLOW	1.0000	ACFM
STANDARD AIR CONDITION-AIR FLOW	0.9938	SCFM
ABSOLUTE HUMIDITY (W)	0.0078	lbs wtr vap/lb da
HUMIDITY RATIO OF MOIST AIR AT SATURATION (Ws)	0.0157	lbs wtr vap/lb da
PARTIAL PRESS OF DRY AIR IN THE MIX (Pa)	29.5526	Inches Hg.
PARTIAL PRESS OF WATER VAPOR IN THE MIX (Pw)	0.3684	Inches Hg.
PARTIAL PRESS: WATER VAPOR SAT. AT W.B. (Px)	0.4927	Inches Hg.
PRESS: SAT. PURE WATER AT DRY BULB (Pws)	0.7369	Inches Hg.
VAPOR PRESS: WATER IN MOIST AIR AT SAT. (Ps)	0.7369	Inches Hg.
MOLE FRACTION OF DRY AIR-IN THE MIX. (Xa)	0.9877	moles da/mole mix
MOLE FRACTION OF WATER-IN THE MIX. (Xw)	0.0123	moles wtr/mole mix
MOLE FRACTION OF WATER VAPOR AT SAT. (Xws)	0.0246	mol vap/mol sat mix
GAS CONSTANT OF DRY AIR IN THE MIXTURE (Ra)	52.9415	
GAS CONSTANT FOR WATER VAPOR (MIXTURE) (Rw)	0.6600	
GAS CONSTANT MIXTURE (R = Ra + Rw)	53.6015	
MOLECULAR WEIGHT OF DRY AIR IN THE MIX.	28.6103	lb mass/mole
MOLECULAR WEIGHT OF THE WATER VAPOR (MIXTURE)	0.2218	lb mass/mole
MOLECULAR WEIGHT OF THE MIX.	28.8322	lb mass/mole
DENSITY OF THE AIR MIXTURE	0.0745	lb wa/ft3 wa
AIR SPECIFIC VOLUME	13.5200	ft3 wa/lb da
AIR FLOW OF THE DRY AIR	4.4379	lbs dry air/hr
WATER VAPOR FLOW	0.0344	lbs wtr vap/hr
WATER VAPOR FLOW @ 100 F	0.0001	gpm
AIR FLOW OF THE MIXTURE	4.4723	lbs wet air/hr
ENTHALPY OF THE DRY AIR IN THE MIXTURE	9.1296	Btu/lb da
ENTHALPY OF WATER VAPOR IN THE MIXTURE	8.4702	Btu/lb da
TOTAL AIR MIXTURE ENTHALPY	17.5998	Btu/lb da
ENTHALPY OF SATURATED STEAM (hg)	1,092.3292	Btu/lb
SENSIBLE HEAT FLOW	40.52	Btu/hr
LATENT HEAT FLOW	37.59	Btu/hr
TOTAL HEAT FLOW	78.11	Btu/hr

TABLE 3—Psychrometric computer analysis for 52 F air temperature.

ELEVATION ABOVE SEA LEVEL	0.	FEET
BAROMETRIC AIR PRESSURE	29.9210	Inches Hg.
DUCTWORK OR GAGE PRESSURE	0.0000	ATMOSPHERIC
TOTAL ABSOLUTE PRESSURE	29.9210	Inches Hg.
DRY BULB AIR TEMEPERATURE	52.0000	F
WET BULB TEMPERATURE	51.1119	F
DEW POINT TEMPERATURE	50.4239	F
ADIABATIC SATURATION TEMPERATURE	51.1162	F
RELATIVE HUMIDITY	94.8157	%
PERCENT SATURATION	94.7511	%
ACTUAL AIR FLOW	1.0000	ACFM
STANDARD AIR CONDITION-AIR FLOW	1.0288	SCFM
ABSOLUTE HUMIDITY (W)	0.0078	lbs wtr vap/lb da
HUMIDITY RATIO OF MOIST AIR AT SATURATION (Ws)	0.0082	lbs wtr vap/lb da
PARTIAL PRESS OF DRY AIR IN THE MIX (Pa)	29.5526	Inches Hg.
PARTIAL PRESS OF WATER VAPOR IN THE MIX (Pw)	0.3684	Inches Hg.
PARTIAL PRESS: WATER VAPOR SAT. AT W.B. (Px)	0.3779	Inches Hg.
PRESS: SAT. PURE WATER AT DRY BULB (Pws)	0.3886	Inches Hg.
VAPOR PRESS: WATER IN MOIST AIR AT SAT. (Ps)	0.3886	Inches Hg.
MOLE FRACTION OF DRY AIR-IN THE MIX. (Xa)	0.9877	moles da/mole mix
MOLE FRACTION OF WATER-IN THE MIX. (Xw)	0.0123	moles wtr/mole mix
MOLE FRACTION OF WATER VAPOR AT SAT. (Xws)	0.0130	mol vap/mol sat mix
GAS CONSTANT OF DRY AIR IN THE MIXTURE (Ra)	52.9415	
GAS CONSTANT FOR WATER VAPOR (MIXTURE) (Rw)	0.6600	
GAS CONSTANT MIXTURE (R = Ra + Rw)	53.6015	
MOLECULAR WEIGHT OF DRY AIR IN THE MIX.	28.6103	lb mass/mole
MOLECULAR WEIGHT OF THE WATER VAPOR (MIXTURE)	0.2218	lb mass/mole
MOLECULAR WEIGHT OF THE MIX.	28.8322	lb mass/mole
DENSITY OF THE AIR MIXTURE	0.0772	lb wa/ft3 wa
AIR SPECIFIC VOLUME	13.0605	ft3 wa/lb da
AIR FLOW OF THE DRY AIR	4.5940	lbs dry air/hr
WATER VAPOR FLOW	0.0356	lbs wtr vap/hr
WATER VAPOR FLOW @ 100 F	0.0001	gpm
AIR FLOW OF THE MIXTURE	4.6296	lbs wet air/hr
ENTHALPY OF THE DRY AIR IN THE MIXTURE	4.8036	Btu/lb da
ENTHALPY OF WATER VAPOR IN THE MIXTURE	8.4097	Btu/lb da
TOTAL AIR MIXTURE ENTHALPY	13.2133	Btu/lb da
ENTHALPY OF SATURATED STEAM (hg)	1,084.5239	Btu/lb
SENSIBLE HEAT FLOW	22.07	Btu/hr
LATENT HEAT FLOW	38.63	Btu/hr
TOTAL HEAT FLOW	60.70	Btu/hr



Material	Given PERM values	Calculated REP values
Outside air film	1000	0.00100
5 in. stone	0.64	1.56250
Air barrier	77	0.01299
0.5 in. exterior plywood	0.5	2.00000
5 in. glass fiber insulation	21.818	0.04583
0.5 in. gypsum board	40	0.02500
Paint	1.5	0.66667
Indoor air film	160	0.00625
		Total: 4.32024

1 Cross-section of wall without vapor barrier.

indoor and outdoor sides of the cavities. Some typical vapor retarder materials are listed in Table 1.

To calculate the amount of water vapor diffusion, the engineer must define the design indoor and outdoor psychrometrics to obtain the needed vapor pressures. If the analysis involves an existing facility, the engineer can test the actual conditions. The properties that must be determined are barometric pressure, gauge pressure, dry bulb temperature, and something to identify moisture in the air, such as wet bulb temperature, dew point temperature, or relative humidity. These properties and the equations to calculate the vapor pressure are illustrated in the accompanying sidebar.

Relative humidity, RH, is a very misunderstood term. It describes the amount of moisture the air holds relative to the maximum it can hold at that temperature. If, for example, the air temperature is 70 F and the relative humidity is, say 50 percent, the air at that temperature contains only 50 percent of the moisture it is capable of holding. If the temperature then drops from 70 to 52 F, the relative humidity increases to 94.8 percent even though the amount of moisture in the air remained unchanged. The reason is that cold air cannot hold as much moisture as warm air. In both cases, however, the absolute humidity, *W* (lb water vapor/lb dry air), is the same.

To summarize, a change in the air dry bulb temperature will cause a shift in the relative humidity even though the amount of moisture in the air remains unchanged. A psychrometric computer analysis of these two conditions are illustrated in Tables 2 and 3. You will also note that the dew point temperature is the same in both cases, which supports the theory that the moisture in the air did not change.

TABLE 4—Psychrometric conditions for Fig. 1 case.

Indoor air	Outdoor air
P_{bar} = 29.2274 in. Hg	P_{bar} = 29.2274 in. Hg
P_{gauge} = 0 in. Hg	P_{gauge} = 0 in. Hg
T_{DB} = 68 F	T_{DB} = 9 F
RH = 50 percent	RH = 50 percent
Pw_1 = 0.23563 in. Hg	Pw_2 = 0.03313 in. Hg

Also, you will note that the vapor pressure is the same in both cases. The vapor pressure, *Pw* (partial pressure of water vapor in the mixture), of the outdoor and indoor air can be calculated by using the equations in the sidebar and by using the steam tables to obtain the pressure of saturated pure water, *Pws*. Using the 70 F/50 percent RH condition (Table 2), we will calculate the vapor pressure of air.

- Given:
  - T_{DB} = 70 F
  - P_{bar} = 29.921 in. Hg
  - P_{gauge} = 0 in. Hg
  - P_{abs} = 29.921 in. Hg
- Calculations:
  - *Pws* = 0.7369 in. Hg (from steam tables)
  - RH = 50 percent = *Pw*/*Pws*
  - *Pw* = 0.3684 in. Hg

The following example will illustrate how to calculate the amount of water vapor diffusion through the wall section and will be used to illustrate the importance of a vapor barrier in this case. The diagram in Fig. 1 is a typical 2 by 6 in. wall section. The materials of construction and air films are shown with their PERM

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TABLE 5—Vapor migration calculation results for a 2 by 6 in. wall without a vapor barrier.

Material description	Thickness, in.	Thermal resistance, *R*, hr-sq ft-F/Btu	Permeance, PERM	Resistance to vapor transmittance, REP (1/PERM)	Surface dry bulb temperature, F	Surface dew point temperature, F	Calculated surface vapor pressure, *Pw*, in. Hg	Saturated air surface vapor pressure, *Px*, in. Hg
Outdoor air					9.00	-5.9089	0.03313	0.06627
Outdoor air film		0.1700	1000.0000	0.00100				
Inner surface					9.4757	-6.3651	0.03318	0.06770
Stone	5.0000	0.1667	0.6400	1.56250				
Inner surface					9.9421	20.2193****	0.10642	0.06912
Air barrier	0.0040	0.0000	77.0000	0.01299				
Inner surface					9.9421	20.3404****	0.10703	0.06912
Exterior plywood	0.5000	0.6200	0.5000	2.00000				
Inner surface					11.6768	34.8143****	0.20077	0.7467
Glass fiber insulation	2.0000	6.9091	60.0000	0.01667				
Inner surface					31.0083	34.9096****	0.20155	0.16929
Glass fiber insulation	3.5000	12.0909	34.2857	0.02917				
Inner surface					64.8383	35.0757	0.20292	0.60344
Gypsum board	0.5000	0.4500	40.0000	0.02500				
Inner surface					66.0974	35.2173	0.20409	0.63044
Paint	0.0024	0.0000	1.5000	0.66667				
Inner surface					66.0974	38.7642	0.23534	0.63044
Indoor air film		0.6800	160.0000	0.00625				
Indoor air					68.0000	39.3304	0.23563	0.67324
Totals	**11.5064**	**21.0867**		**4.3202370**				

Total water vapor transmission: 0.04687193430045 grains/sq ft-hr or 0.00000669599 lb/sq ft-hr.
Sensible heat transfer through the roof (negative value indicates flow from outside to inside): 2.7980 Btu/sq ft-hr.
Indoor air conditions: 68 F/35 percent RH.
Outdoor air conditions: 9 F/50 percent RH.
Elevation: 680 ft.

****If *Pw* is greater than or equal to *Px*, condensation will occur in that region.
****If the dew point temperature is greater than or equal to the dry bulb temperature, condensation will occur.

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TABLE 6—Vapor migration calculation results for a 2 by 6 in. wall with a vapor barrier.

Material description	Thickness, in.	Thermal resistance, *R*, hr-sq ft-F/Btu	Permeance, PERM	Resistance to vapor transmittance, REP (1/PERM)	Surface dry bulb temper-ature, F	Surface dew point temper-ature, F	Calculated surface vapor pressure, *Pw*, in. Hg	Saturated air surface vapor pressure, *Px*, in. Hg
Outdoor air					9.00	-5.9089	0.03313	0.06627
Outdoor air film		0.1700	1000.0000	0.00100				
Inner surface					9.4757	-6.3873	0.03315	0.06770
Stone	5.0000	0.1667	0.6400	1.56250				
Inner surface					9.9421	3.1351	0.05196	0.06912
Air barrier	0.0040	0.0000	77.0000	0.01299				
Inner surface					9.9421	3.2000	0.05211	0.06912
Exterior plywood	0.5000	0.6200	0.5000	2.00000				
Inner surface					11.6768	11.6040	0.07619	0.7467
Glass fiber insulation	2.0000	6.9091	60.0000	0.01667				
Inner surface					31.0083	11.6631	0.07639	0.16929
Glass fiber insulation	3.5000	12.0909	34.2857	0.02917				
Inner surface					64.8383	11.7669	0.07674	0.60344
Poly vapor barrier	0.0040	0.0000	0.0800	12.50000				
Inner surface					64.8383	37.8835	0.22723	0.60344
Gypsum board	0.5000	0.4500	40.0000	0.02500				
Inner surface					66.0974	37.9167	0.22753	0.63044
Paint	0.0024	0.0000	1.5000	0.66667				
Inner surface					66.0974	38.7875	0.23556	0.63044
Indoor air film		0.6800	160.0000	0.00625				
Indoor air					68.0000	39.3304	0.23563	0.67324
Totals	11.5104	21.0867		16.8202370				

Total water vapor transmission: 0.01203894247757 grains/sq ft-hr or 0.00000171985 lb/sq ft-hr.
Sensible heat transfer through the roof (negative value indicates flow from outside to inside): 2.7980 Btu/sq ft-hr.
Indoor air conditions: 68 F/35 percent RH.
Outdoor air conditions: 9 F/50 percent RH.
Elevation: 680 ft.

and REP values. You will note that this wall does not have an indoor vapor retarder. Psychrometric conditions for this analysis are shown in Table 4. Using this information and the summation of the REP values in Fig. 1, we can calculate the amount of water vapor flow:

$W = (1/4.32024) \times (0.23563 - 0.03313) = 0.04687$

The diffusion of water vapor through this wall is 0.04687 grains of water vapor per hr per sq ft of wall surface. Now let's determine what happens if we add a 4 mil vapor barrier between the gypsum board and glass fiber insulation. A 4 mil polyethylene vapor barrier has a PERM of 0.08 or a REP of 12.5. This increases the REP summation to 16.82024. Now let's recalculate the amount of water vapor diffusion through the cavity:

$W = (1/16.82024 \times (0.23563 - 0.03313) = 0.012039$

You can see that without the vapor barrier, the amount of water vapor diffusion through the cavity is 3.89 times higher or, in other words, 289 percent higher than the wall with the vapor retarder. This is a significant change, but is it needed?

To answer this question, we put the parameters into a computer program that calculates the surface temperatures of all the materials and also calculates the surface dew points to check for condensation. If condensation occurs, the program prints out stars next to the calculated surface dew point temperatures. Table 5 shows the results of the computer analysis for the wall without the vapor barrier, and Table 6 is with a vapor barrier. Without the vapor barrier, you can see that condensation does exist. Since water vapor is moving from inside to outside, you can see that it starts at the glass fiber insulation. The condensation may stop at the glass fiber insulation due to the reduction of vapor flow through the remaining materials. If, however, the condensation is frequent, it could cause a loss of insulating value (R-value), which could cause the condensation to move into the adjacent materials. The wall with the vapor barrier (Table 6) has no condensation.

Example cases

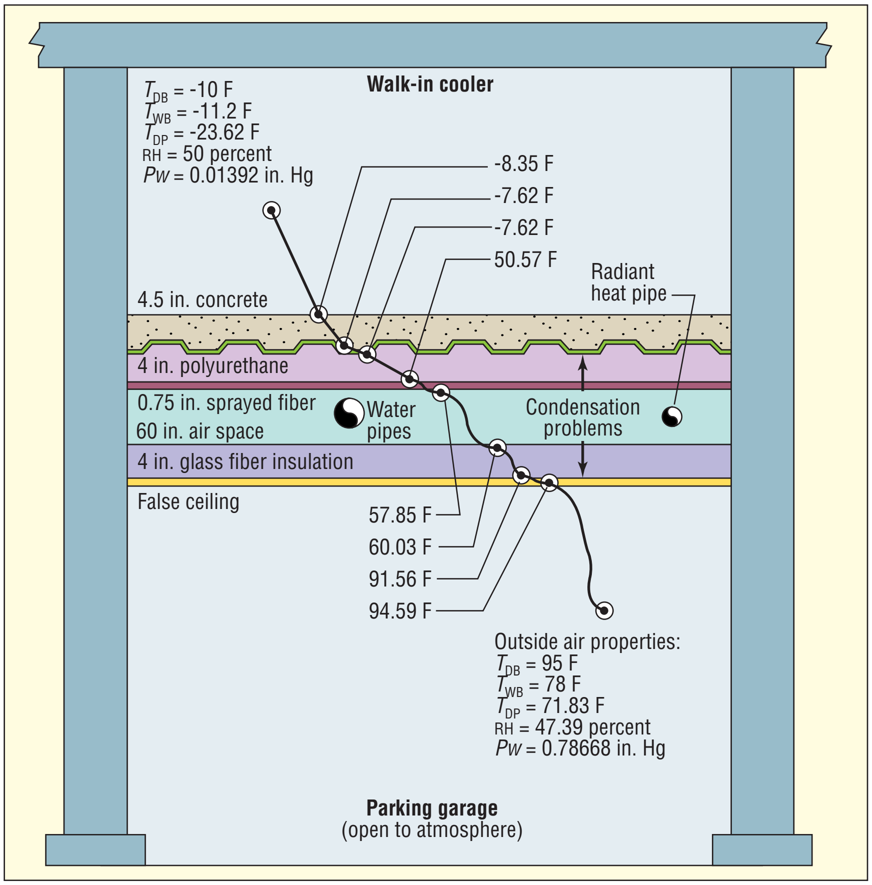
Freezer and cold storage facilities require a lot of attention to design details. The indoor vapor pressures can be as low as 0.011 in. Hg, resulting in vapor pressure differentials as high as 0.78 in. Hg, which is three to four times higher than the differentials experienced in residential and commercial buildings. Vapor retarders are critical to reduce the moisture drive into the freezer and to prevent condensation. One client had major condensation problems from the underside of a supermarket floor. The supermarket was built with parking at ground level; the cold freezer facilities and supermarket were on the second floor above the parking area. The parking area is totally open to the outdoor environment. One area that had condensation problems was the underside of a walk-in cooler floor. An elevation sketch of the construction is shown in Fig. 2.

The problem was condensation in the false ceiling air cavity. The glass fiber insulation shown on top of the false ceiling would get so wet with moisture it would collapse the false ceiling into the parking area. Surface temperatures based on heat loss calculations are also illustrated in Fig. 2.

From these temperatures, you can see that during the summer, the glass fiber insulation was preventing heat gain into the air space. This is a problem because the surface temperatures are well below the outside air dew point temperature. With no vapor barrier and the poor air tightness of the false ceiling, the air cavity will have a dew point very close to the outside air dew point. This, in turn, results in condensation because the vapor can touch a surface that is below its dew point.

One solution might be to remove the glass fiber insulation. In this case, however, it is not possible because the air cavity must be heated in winter to prevent freezing of the pipes in the air space. This is why the diagram shows radiant heat pipes. The solution used was to run the radiant heat system in the summer, which raises the surface temperatures above the dew point temperature. To save energy, one could install sensors to monitor the metal deck temperature and the dew point temperature. A controller could then turn on the radiant heat to maintain the surface at 5 F higher than the dew point temperature.

The computer condensation analysis program revealed con-



2 Surface temperatures through the floor along with inside and outside air properties.

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densation problems inside the false ceiling.

One industry that has many problems with water vapor diffusion and condensation is the paper industry. The wet end section of a paper machine takes the water and fiber and forms it into a sheet. The stock temperature is around 100 to 120 F; therefore, the evaporation rate into the building is high. The dry end section, unlike the wet end section, has a hood to capture the water evaporated and discharges the water vapor outside. Some of these hoods, however, have leaks that can raise the humidity excessively inside the building. The molecular weight of water vapor is less than the molecular weight of dry air. Therefore, the water vapor rises to the underside of the paper machine building roof, thus raising the dew point at the underside higher than the rest of the building.

At one mill location, the air properties taken at the underside of the roof were as follows:

- P_{bar} = 29.8220 in. Hg
- T_{DB} = 111 F
- T_{WB} = 103.33 F
- T_{DP} = 102.05 F
- RH = 77 percent
- Pw = 2.0553 in. Hg

This particular machine room had little dryer hood leakage.

Another survey for a machine room housing five paper machines showed a lot of condensation, corrosion, and spalling of concrete from the roof deck. A mass air and water vapor survey of the building revealed a water vapor flow into the building of 123,175 lb per hr or 248 gpm. As you can imagine, this raised the building humidity to extreme levels. The worst area tested—at the underside of the roof—is illustrated below:

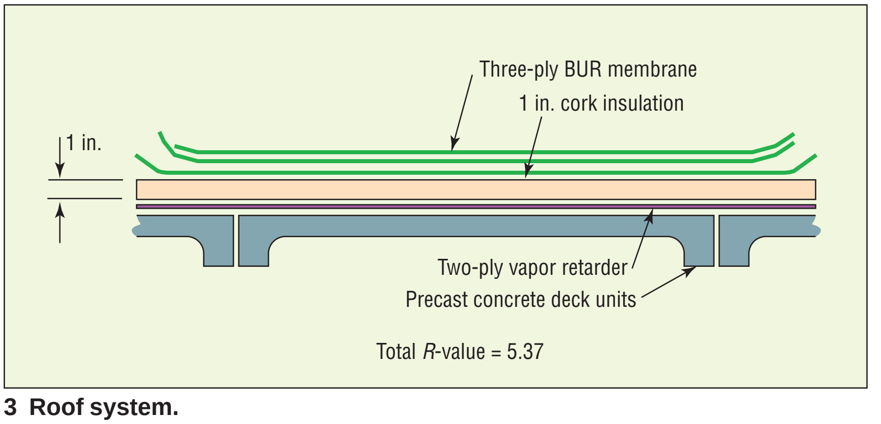
- P_{bar} = 29.8220 in. Hg
- T_{DB} = 159 F
- T_{WB} = 136.51 F
- T_{DP} = 135 F
- RH = 54.81 percent
- Pw = 5.1651 in. Hg

The vapor pressure differential across the roof system in this case is over 4.0 in. Hg, which is tremendous as well as unacceptable. The theory behind preventing roof surface condensation is to keep the inside roof surface temperature above the dew point temperature of the vapor rising to the ceiling. The surrounding air dry bulb temperature heats the roof surface, but due to heat loss through the roof, the surface temperature will always be lower than the dry bulb temperature. One method of raising the roof surface temperature is to add insulation to the roof. If you look back to the first paper mill example, you can see that the dew point is 102 F and the dry bulb is 111 F. Therefore, in this case, you can expect the roof temperature to be less than 111 F but hopefully not at or below 102 F.

To help prevent condensation in today's machine rooms, one should supply a roof heating system for the underside of the building roof. Roof heating systems are air handling units that take indoor building air, heat it to 120 F, and distribute it to the underside of the building roof. Depending upon roof insulation levels, this process will then heat the roof to around 110 to 115 F. Certainly, the building does not need any more heat, but it is required until the industry puts a hood on the wet end section. If you look back at the five paper machine building example, you will note that the dew point was at 135 F, which is well above the temperature of the existing roof heating system. In this case, the roof heating system does not prevent condensation. The cure to the condensation problem is to find the hood leaks and patch them.

The problems with water vapor condensation inside the machine rooms are complex and require further review. The water vapor transmission is tremendous due to the high vapor pressure differentials. The next problem is to design the roof system so that the vapor can escape without condensation or to have the vapor condense in a safe region. Over 45 percent of the roof failures are caused by poor roof design. Vapor retarders are a necessity.

An example of a paper machine building roof is illustrated in Fig. 3. The psychrometric test conditions at the underside of the building roof were illustrated in the first example. This mill was experiencing condensation and concrete deck spalling. The design conditions were put into the condensation analysis program to check for problems. The results can be found in Table 7.



3 Roof system.

The program shows condensation in the concrete roof deck. This explains the roof spalling problems. In this case, there was insufficient insulation in the roof, resulting in a low inside roof surface temperature. The steel reinforcement in pre-cast concrete decks will corrode when exposed to condensation and chemicals such as chlorine. Test samples taken from concrete decks have shown acid-soluble chlorine-ion contents of between 100 and 1100 ppm of concrete. Special precautions need to be taken to prevent the corrosion of steel reinforcement.

Poor conditions at the underside of a paper machine building roof should not be taken lightly. High humidities will result in premature failure of the roof support steel, concrete deck, and roofing materials. Some mills have experienced complete failures just a few years after installation, and others have had roof sections fall into the paper machines. To give you an idea of the costs, a mill in the south had to replace the roof steel, concrete deck, and roofing materials at a cost of over $1,000,000 or about $50 per sq ft of roof. The building housed a tissue machine, and the replacement occurred 24 years after installation.

The last example will illustrate blower door surveys, infrared surveys, the use of mass dry air and water vapor analysis, and adiabatic mixing to solve condensation problems in buildings. It was kept simple so that the analysis would fit into this article. The building is a residential home with severe attic condensation problems in the winter. The home has cathedral ceilings of tongue-and-groove maple panels. The home had condensation in the attic that dripped through the ceiling. The contractor told the homeowner that the problem was the storage of 22 face cords of firewood in the basement.

The first test conducted was a blower door test to determine the building air change rate. The

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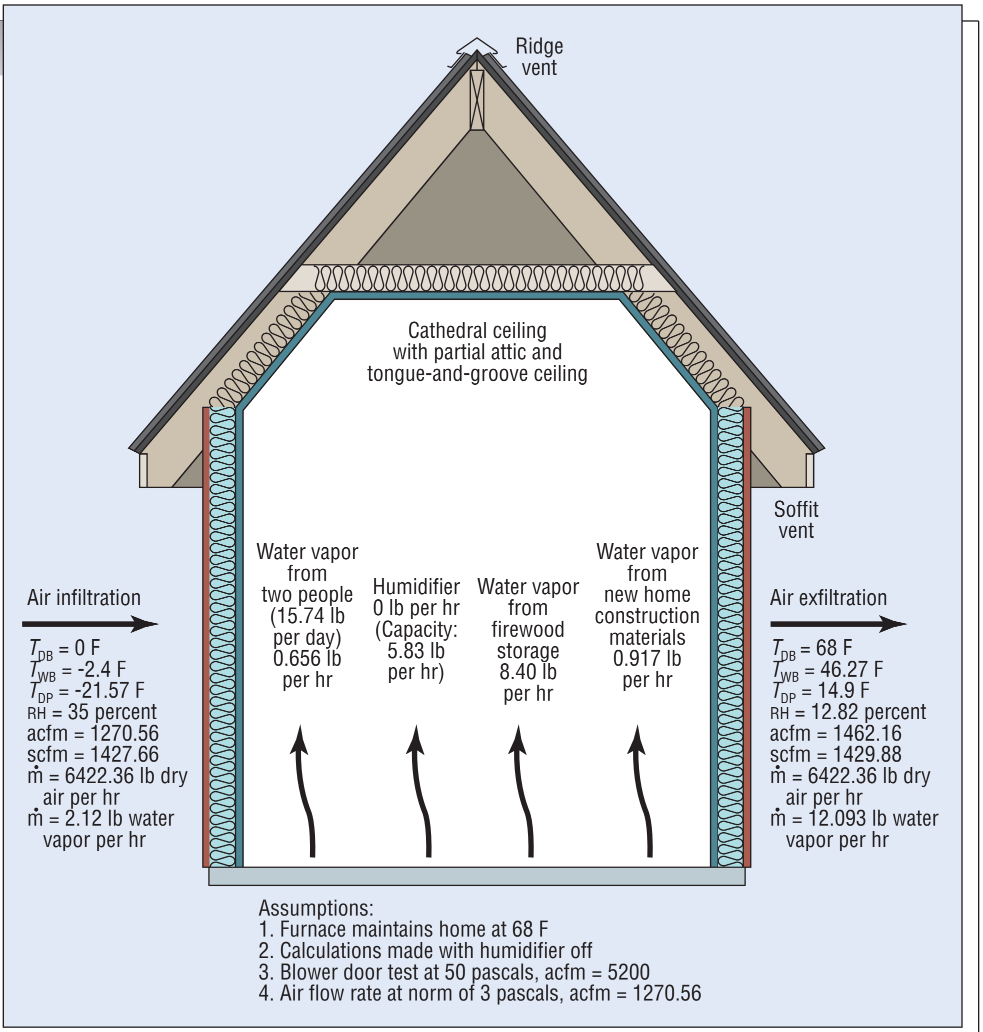
TABLE 7—Vapor migration calculation results for a paper mill roof (Fig. 3).

Material description	Thickness, in.	Thermal resistance, *R*, hr-sq ft-F/Btu	Permeance, PERM	Resistance to vapor transmittance, REP (1/PERM)	Surface dry bulb temperature, F	Surface dew point temperature, F	Calculated surface vapor pressure, *Pw*, in. Hg	Saturated air surface vapor pressure, *Px*, in. Hg
Outdoor air					19.00	11.1422	0.07450	0.10493
Outdoor air film		0.1700	1000.0000	0.00100				
Inner surface					21.9125	11.0681	0.07450	0.11876
3-ply BUR membrane	0.4000	0.3300	0.0100	100.00000				
Inner surface					27.5661	16.3818	0.09406	0.15030
Cork insulation	1.0000	3.8500	2.1000	0.47619				
Inner surface					93.5251	16.4043	0.09415	1.58068
2-ply vapor retarder	0.4000	0.3300	0.0001	10,000.00000				
Inner surface					99.1788	101.4590****	2.04965	1.87862
Pre-cast concrete deck	1.0000	0.0800	3.2000	0.31250				
Inner surface					100.5493	101.4600****	2.04972	1.95776
Indoor air film		0.6100	160.0000	0.00625				
Indoor air					111.0000	102.0828	2.04972	2.66197
Totals	2.8000	5.3700		10,100.7959405				

Total water vapor transmission: 0.00019555046821 grains/sq ft-hr or 0.00000002794 lb/sq ft-hr.
Sensible heat transfer through the roof (negative value indicates flow from outside to inside): 17.1322 Btu/sq ft-hr.
Indoor air conditions: 111 F/77 percent RH.
Outdoor air conditions: 19 F/71 percent RH.
Elevation: 90 ft.

****If *Pw* is greater than or equal to *Px*, condensation will occur in that region.
****If the dew point temperature is greater than or equal to the dry bulb temperature, condensation will occur.



4 Mass flow balance.

blower door air flow was 5200 cfm at a differential pressure of 50 pascals (0.201 in. WG). The calculated air change rate in air changes per hour (ACH) is as follows:

ACH = (acfm × 60 min per hr)/(Building volume, cu ft/1 air change) = (5200 × 60)/(21,693/1) = 14.4

This is a high air change rate for a new home.

The next step was to determine where the air flow paths were. An infrared-image heat-loss scan was conducted with the blower on and with the blower door off to help accentuate the areas with air flow heat loss. The infrared-image scans showed air flow leaking through the tongue-and-groove ceiling panels. It was discovered later that the kraft-back vapor barrier was not stapled against the inside face of the cathedral ceiling rafters. Instead, the vapor retarder was stapled to the inner sides of the rafters. If the vapor retarder is installed against the inside face of the rafter and the tongue-and-groove paneling is nailed against the vapor retarder, you can achieve air tightness. This was not done. Without air tightness, you have a potentially dangerous situation because air flow can carry much more moisture into the attic than diffusion through the materials. The amount of water vapor diffusion through 1364 sq ft of ceiling in this case is 0.01438 lb of water vapor per hr.

The blower door air flow of 5200 cfm was converted to air flow at normal building differential pressure of 3 pascals (0.012 in. WG), which is 1270 acfm. If all of this air flow travels through the tongue-and-groove ceiling into the attic, the water vapor it carries will be 23.70 lb per hr if the home is maintained at 68 F/35 percent RH. This amount of water vapor flow is 1648 times higher than the water vapor diffusion into the attic. If the house was built with the proper air tightness, the air flow at 3 pascals would be around 289 acfm. Therefore, the excess air flow through this house comes to 981 acfm. If we instead assume that only 1 percent of the excess air flow goes into the attic, the amount of water vapor it would carry is still 16 times higher than the diffusion flow. What this illustrates is that air tight construction is extremely important.

The next step was to conduct a mass flow analysis using the tested air flow at 3 pascals, an indoor design temperature of 68 F, and estimates of water vapor generation inside the home. The outside winter air is assumed to be 0 F/35 percent RH. To conduct a mass flow analysis, one must convert the flows to pounds of dry air and pounds of water vapor. Therefore, the amount of dry air entering must be equal to the amount of dry air leaving. This is not the case with acfms. The finalized analysis is illustrated in Fig. 4.

You will note that the storage of firewood in the home did add a tremendous vapor load. What is even more interesting is that the calculated indoor humidity (air leaving) is only 12.8 percent, even with all this water vapor load. This condition was verified by the homeowner who said that the humidifier had to run frequently because the house was so dry. The reason for the dry environment is the excessive outside air flow into the house, which was drying out the house. Further investigations revealed similar homes that were very hard to heat due to the excess air flow.

To summarize, the condensation problem was due to the air and water vapor flow into the attic. The amount of water vapor entering the attic was too much for the attic to handle, which raised the air dew point, causing the condensation. This is why state codes emphasize air tightness.

Conclusion

Due to space limitations, this article only covered some of the basics of water vapor analysis and control. The use of vapor retarders, for instance, gets professionals into very heated and complex debates. Certainly, there are times when vapor retarders are needed and times when they are not. To help engineers with these decisions, the U.S. Army Cold Regions Research Laboratory (CRREL) has developed a procedure, information about which can be obtained from the National Roofing Contractors Association in Rosemont, Ill. Also, there is a paper written by the staff of the Oak Ridge National Laboratory, Oak Ridge, Tenn., that provides new information about vapor retarder selection criteria.

This is a difficult field that could use additional research work to assist the engineers' efforts. It is also a field that is getting a lot of attention these days due to the concern of indoor air quality.

For engineers who want to learn more about moisture transport modeling for buildings, the *1997 ASHRAE Handbook of Fundamentals* recommends the following but warns that most of the models are research tools that may be too complex for users other than researchers:

- Glasta (Physibel, Belgium)
- EMPTEDD (Trow, Toronto, Canada)
- Match (Technical University, Lyngby, Denmark)
- COND (Technical University, Dresden, Germany)
- MOIST (NIST, Gaithersburg, Md.) **HPAC**

Questions or comments about this article may be directed to the author at 920-465-3548.

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